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**GEORGIA INSTITUTE OF TECHNOLOGY  
OFFICE OF CONTRACT ADMINISTRATION  
SPONSORED PROJECT INITIATION**

Date: May 1, 1978

Project Title: *Nuclear and X-Ray Spectroscopy with Radioactive Sources*

Project No: *G-33-632*

Project Director: *Dr. R.W. Fink*

Sponsor: *Department of Energy; Oak Ridge Operations; Oak Ridge, Tennessee 37830*

Agreement Period: From 2/1/78 Until 1/31/79 (Contract Period)

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Sponsor Contact Person (s):

Technical Matters

Contractual Matters  
(thru OCA)

*Mr. Walker Love/Mr. Earl Mason  
Research Contracts, Procedures & Reports Branch  
Contract Division  
U.S. Department of Energy  
Oak Ridge Operations  
P.O. Box E  
Oak Ridge, Tennessee 37830  
Phone (615) 483-8611*

NOTE: *FOLLOW-ON PROJECT TO G-33-622 (MOD. A013)*

Defense Priority Rating: *None*

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GEORGIA INSTITUTE OF TECHNOLOGY  
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*Fast  
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Date: May 22, 1979

Project Title: Nuclear and X-Ray Spectroscopy with Radioactive Sources

Project No: G-33-632 (continuation of G-33-622)

Project Director: Dr. R. W. Fink

Sponsor: U. S. Department of Energy; Oak Ridge Operations;  
Oak Ridge, TN 37830

Effective Termination Date: 1/31/79 (Mod. A014 Period)

Clearance of Accounting Charges: 1/31/79

Grant/Contract Closeout Actions Remaining:

**TERMINATED**

- ☒ Final Invoice ~~and Closing Document~~
- ☒ Final Fiscal Report (Annual Statement of Costs)
- ☐ Final Report of Inventions
- ☐ Govt. Property Inventory & Related Certificate
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NOTE: FOLLOW-ON PROJECT WILL BE G-33-645.

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# **NUCLEAR AND X-RAY SPECTROSCOPY WITH RADIOACTIVE SOURCES**

**Fourteenth Annual Progress Report  
U. S. Department of Energy  
Contract EY-76-S-05-3346**

**R. W. Fink  
Professor of Chemistry & Principal Investigator  
and  
John L. Wood  
Research Scientist & Co-principal Investigator**

**October 31, 1978**

**GEORGIA INSTITUTE OF TECHNOLOGY  
SCHOOL OF CHEMISTRY  
ATLANTA, GEORGIA 30332**

1978



**Tel. (404) 894-4030**

## ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DOE  
CONTRACT NO.  
EY-76-S-05-3346SUPPORTING DIV. OR OFFICE: Basic Energy Sciences

NAME &amp; ADDRESS OF CONTRACTOR OR INSTITUTION: (State the division, department, or professional school, medical, graduate or other, with which this project should be identified.)

School of Chemistry  
Georgia Institute of Technology  
Atlanta, Georgia 30332

TITLE OF PROJECT:

NUCLEAR AND X-RAY SPECTROSCOPY WITH RADIOACTIVE SOURCES

(1979/80)

NAMES, DEPARTMENT, AND OFFICIAL TITLES OF PRINCIPAL INVESTIGATORS AND OTHER PROFESSIONAL SCIENTIFIC PERSONNEL: (not including graduate students) engaged on the project, and fraction of man-year devoted to the project by each person.

Dr. R. W. Fink, Professor and Principal Investigator  
Dr. John L. Wood, Research Scientist and co-principal investigator  
Dr. Robert A. Braga, Postdoctoral Associate  
Dr. Warren R. Western, Postdoctoral Research Associate

NO. OF GRADUATE STUDENTS ON PROJECT: 4 NO. OF GRADUATE STUDENT MAN-YEARS: 2

SUMMARY OF PROPOSED WORK: (200-300 words, omit Confidential Data). Summaries are exchanged with government and private agencies supporting research, are supplied to investigators upon request, and may be published in documents. Make summaries substantive, giving initially and for each annual revision the following: OBJECTIVE; SCIENTIFIC BACKGROUND FOR STUDY; PROPOSED PROCEDURE; TEST OBJECTS AND AGENTS.

This program is a systematic study of nuclei far from stability with radioactive sources produced with heavy ions from the Oak Ridge Isochronous Cyclotron and mass-separated on-line by the UNISOR facility. Such experiments complement in-beam reaction spectroscopy (which is confined to high-spin states) and are the only means of exploring the low-spin structure of nuclei far from stability. This research investigates: (1) core-particle coupling models and the role of the Fermi energy; (2) shapes of transitional nuclei; (3) pairing correlations in transitional nuclei; (4) shape and pairing isomerism; (5) shell model intruder states; and (6) proton-neutron correlations; as well as a search for new radioactive nuclides. Currently the emphasis is on transitional regions bordering  $Z = 82$  (isotopes of Pt, Au, Hg, Tl, Bi, and Po).

These studies are complemented on-campus by related work on x rays from radioactive sources (fluorescence and Coster-Kronig yields for  $Z = 64-83$ ), lifetimes of certain nuclear excited states, computer codes for data analysis, and radioactive nuclides produced in the 5 MW Georgia Tech Research Reactor.

RESULTS TO DATE: Summarized in the Annual Progress Report, OR0-3346-223 (Oct.31, 1978)

For 1977/78, there were 18 publications appearing in the literature or in press, and one Ph.D. thesis will be completed December, 1978 (M. A. Grimm), based on UNISOR work under an ORAU fellowship.

	PROGRAM CATEGORY NO.
BUDGET	
PRIMARY	
SECONDARY	

Signature of Principal Investigator

DATE: SEP 13 1978

INVESTIGATOR -- DO NOT USE THIS SPACE

NUCLEAR AND X-RAY SPECTROSCOPY WITH RADIOACTIVE SOURCES

Fourteenth Annual Progress Report

U. S. Department of Energy

Contract EY-76-S-05-3346

R. W. Fink

Professor of Chemistry and Principal Investigator

and

John L. Wood

Research Scientist and Co-principal Investigator

October 31, 1978

School of Chemistry

Georgia Institute of Technology

Atlanta, Georgia 30332

Telephone: (404) 894-4030

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NUCLEAR AND X-RAY SPECTROSCOPY WITH RADIOACTIVE SOURCES  
14th Annual Progress Report

R. W. Fink Professor and Principal Investigator

and

John L. Wood, Research Scientist and Co-principal Investigator

October 31, 1978

## 1.0 INTRODUCTION

One of the major areas of our research program for this year has been the experimental confirmation (utilizing the UNISOR facility at Oak Ridge) and extension of the nuclear systematics and models that we have been investigating for the last several years in the regions adjacent to the  $Z = 82$  closed shell.

The systematic features of the odd-mass Hg isotopes have been elucidated, based upon the Ph.D. thesis of G. M. Gowdy. The coupling of the  $i_{13/2}$  quasiparticle to the (triaxial) core shows a simple dependence on the Fermi energy, in agreement with the predictions of the Meyer ter Vehn model. Some simple rules have been developed for the use of nuclear systematics, and their use suggests a number of low-lying states in  $^{187}\text{Hg}$ ,  $^{187}\text{Au}$ , and  $^{185}\text{Au}$  are strongly-deformed prolate (Nilsson) ones, coexisting with the many weakly-deformed oblate triaxial (shell-model) states, characteristic of this transitional region. Also, in the case of  $^{187}\text{Au}$ , we have evidence for different types of oblate triaxial states, resulting from the coupling of the  $h_{9/2}$  proton particle to the  $^{186}\text{Pt } 0_1^+$  (ground state) and  $0_2^+$  (475 keV) configurations. Our results suggest that the two types of structure differ significantly in their pairing structure or in their inertial mass structure. The study of the  $A = 187$  isobaric chain constitutes the Ph.D. thesis research of one of our graduate students, Mr. Marvin Grimm, who is in residence at Oak Ridge as an ORAU fellow.



We have pursued the properties of intruder states above the  $Z = 82$  shell closure, and we find the  $s_{1/2}$  hole states in  $^{199,201}\text{Bi}$  as isomers. In  $^{201}\text{Bi}$  we observe decay to the  $h_{9/2}$  particle ground state by an M4 isomeric transition, with  $B(M4)$  retarded by a factor of about 4500 relative to the Weisskopf estimate. A compilation of  $B(M4)$  values has been made for all known cases in odd-A nuclei (75 cases), and only  $^{199,201}\text{Bi}$  are retarded. Possible explanations of this highly unusual phenomenon, involving hole  $\rightarrow$  particle and/or possible  $\ell$ -forbiddenness, are discussed below. In the region beyond  $Z = 82$  we have also started to study the structure of the Po isotopes populated by decay from  $^{201-205}\text{At}$  parents. This constitutes part of the Ph.D. thesis research of Mr. Chris Papanicolaopolos. In connection with studies of intruder states, the fast coincidence timing equipment at Georgia Tech has been used in lifetime measurements of members of the  $g_{7/2}$  intruder band in  $^{109}\text{Ag}$  populated by decay of  $^{109}\text{Pd}$  sources prepared in the Georgia Tech Reactor.

Our investigation of quadrupole pairing and the possibility of proton pair-neutron pair interactions continues. The microscopic picture emerging for an interacting boson approximation (IBA) for collective motion in nuclei (Iachello, Arima, Talmi, and Otsuka) strongly suggests that this correlation of neutron and proton pairs is directly related to the interaction of proton and neutron bosons in the IBA. Our understanding of the IBA has benefitted from the attendance by J. L. Wood at the "Workshop on the Interacting Boson Approximation" held in Erice, Sicily, June 6-9, 1978.

During the year J. L. Wood spent 2 1/2 months with the Isotope Separator group at GSI-Darmstadt, West Germany, working on  $\gamma$ -ray spectroscopy of decays of light iodine and lead isotopes, in a collaboration with E. Roeckl and our former graduate student, G. M. Gowdy.

This year considerable progress has been made in software development for both our Nuclear Data ND-4420 system and the CDC-Cyber 70 central computer at Georgia Tech, in order to enable UNISOR data to be evaluated in our laboratory using the ND-4420 system.

Our long-standing investigation of  $L_2$ - $L_3$  Coster-Kronig transition probabilities and subshell x-ray fluorescence yields has been revived in a study at  $Z = 64$  and  $67$ , due to significant improvements in both the experimental technique and experimental determination of tailing corrections. This work constitutes part of the thesis research of Mr. Bruce Gnade.

Following below are further details and references to work highlighted above and to additional work.

## 2.0 NUCLEAR SPECTROSCOPY

### 2.1 Nuclear Systematics and Models

Our use of nuclear systematics and simple models has matured considerably in the past year. We have been developing nuclear systematics as a tool for a number of years and have now arrived at a set of simple rules (ref. 15) which permits detailed nuclear structures (single-particle states, collective states) to be followed from the region of stability, where a rich variety of spectroscopic information is available (e.g., one- and two-nucleon transfer reactions, Coulomb excitation), to the far beta-unstable regions. The set of rules currently in use is:

(i) If  $E(4_1+)/E(2_1+) > 3.1$ , the Nilsson model and the rigid rotator can be used;

(ii) For odd-proton (-neutron) nuclei: Use of isotope (isotone) systematics must be made. A changing Fermi energy is very difficult to systematize unless the Nilsson model is applicable to the region;

(iii) If  $\Delta E(2_1+)/E(2_1+) > 10\%$  for a change of two mass units, great caution is needed when following systematic trends (however, few nuclei away from closed shells exhibit this);

(iv) Odd-proton nuclei near closed shells possess shell model intruder states with well-defined band structures, which appear below 1 MeV;

(v) For transitional nuclei the rigid triaxial rotor model of Meyer and Vehn is an excellent basis for systematization in that it predicts the correct number of states, adequately describes trends in changing shapes, and is simple to use;

(vi) Above the pairing gap, only yrast states and intruder states can be systematized.

In practice, what these rules dictate is that a particular excitation in a given nucleus will appear in a neighboring nucleus (differing by two protons or two neutrons) with only minor changes in its properties, particularly its energy. By minor is meant, for example, the energy of the state relative to the ground state is the same in the two nuclei within about 50 keV. The power of this set of rules is that new degrees of freedom entering a particular nuclear region are readily identifiable. We discuss the application of these rules (and exceptions to them) in the region  $183 \leq A \leq 203$  for special cases below.

In last year's annual report (ORO-3346-214), we described in some detail the behavior of the  $h_{9/2}$  intruder state in the odd-mass Tl, Au, and Ir nuclides. The conclusion was that, due to quadrupole pairing, excitation of the odd proton into the  $h_{9/2}$  intruder orbital removes the blocking effect for proton pairing correlations and permits proton pair — neutron pair correlations to occur. In the past year we have been trying to understand the nature of this completely

new type of correlation. A clue is now available from the microscopic model of the interacting boson approximation (IBA)<sup>a)</sup>. In this model, the bosons are

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<sup>a</sup> A. Arima, et al., Phys. Lett. 66B, 205 (1977)

T. Otsuka, et al., Phys. Lett. 76B, 139 (1978)

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described by nucleon pairs and are of two types, proton bosons and neutron bosons. The central feature of the model is the importance of the interaction between these two kinds of bosons. We are now exploring the possibility that what we observe in the  $h_{9/2}$  intruder state behavior in the Tl, Au, Ir region is a manifestation of this proton-neutron (pair or boson) interaction.

(J. L. Wood)

## 2.2 Completed Experimental Studies

### 2.2.1 Odd-Mass Hg Decays

The preparation for publication of our results from the decay scheme studies of  $^{189,191,193}\text{Hg}$  continues. Owing to our plans to study further the excited states of the nucleus  $^{189}\text{Au}$  (see the accompanying renewal proposal), we will publish our results to date in two papers: one on the decay scheme of  $^{193g}\text{Hg}$  and one on the systematic features and theoretical interpretation of the odd-mass Au nuclei (which will include our  $^{189,191}\text{Au}$  results).

### 2.2.2 Odd-Mass Tl Decays

In the past year we have successfully elucidated the systematic features of the excited states of the odd-mass Hg isotopes populated in the decays of  $^{187-197}\text{Tl}$ . The key to this was the identification of the positive parity states, which constitute triaxial bands built on the  $i_{13/2}$  neutron quasiparticle. Although the Fermi energy is changing through these isotopes, it is the occupancy of the  $i_{13/2}$  subshell alone that is changing. Further, the core shapes (represented by the neighboring doubly-even Hg isotopes) are

essentially constant, and thus the systematic trends are described by the Meyer ter Vehn triaxial rotor model with a single variable - the changing Fermi energy. This is a rare exception to systematics rule ii above and is the first time that the dependence of the Meyer ter Vehn model on the Fermi energy has been explored over a broad sequence of nuclei. A letter on the  $i_{13/2}$  band systematics in the odd-mass Hg isotopes is in preparation<sup>b)</sup>.

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<sup>b</sup> "The Positive Parity States in  $^{187-199}\text{Hg}$  Isotopes," J. L. Wood, G. M. Gowdy, and R. W. Fink, Phys. Rev. Lett. (to be submitted)

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Our study of the decay scheme of  $^{195}\text{Tl}$  is in press (ref. 1), and of  $^{197}\text{Tl}$  is about to be submitted<sup>c)</sup>. The decay schemes of  $^{193}\text{Tl}$  and  $^{191}\text{Tl}$  are being finalized. We plan to conduct further measurements on the decays of  $^{189,187,185}\text{Tl}$  (see the accompanying renewal proposal).

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<sup>c</sup> "Decay of  $^{197}\text{Tl}(2.83\text{ h})$  to  $^{197}\text{Hg}$ ," R. A. Braga, J. L. Wood, G. M. Gowdy and R. W. Fink, Nuclear Phys. A (to be submitted)

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### 2.2.3 Odd-Mass Pb Decays

The studies of the decay schemes of  $^{193,195,197}\text{Pb}$  have been completed and submitted for publication (refs. 8, 13, 14).

### 2.2.4 The Decay of 43 sec $^{183\text{m}}\text{Pt}$

In the past year we have begun studies in the  $A = 183$  mass chain. We find a very simple fast beta-decay mode involving the Nilsson states  $\nu 7/2-[514]$  and  $\pi 9/2-[514]$  for an isomer in  $^{183}\text{Pt}$ . Details of this work are in press (ref. 12). We note that the observation of the Nilsson state  $\nu 7/2-[514]$  in  $^{183}\text{Pt}$  is an exception to our systematics rule i. There is clear

evidence that the odd-mass Pt isotopes<sup>d)</sup> with  $A \leq 185$  behave like the odd-mass Hg isotopes<sup>e)</sup> with  $A \leq 185$ , in that they are strongly prolate-deformed, whereas the even-mass Pt and Hg neighbors are weakly oblate-deformed, indicating shape isomers nearly degenerate in energy (see Sect. 2.3.1 below)

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<sup>d</sup> E. Hagberg, et al., to be published in Phys. Lett.

<sup>e</sup> J. Bonn, et al., Z. Physik A276, 203 (1976)

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## 2.3 Current Experimental Studies

### 2.3.1 Decay of $^{185,187}\text{Hg}$ Isotopes

Our detailed experimental work on the extraordinarily complex decay scheme of the  $^{187m,g}\text{Hg}$  isomers to excited states of  $^{187}\text{Au}$  are nearing completion. This constitutes the major part of the Ph.D. thesis of Mr. Marvin Grimm, who is at UNISOR as an ORAU fellow. The structure of  $^{187}\text{Au}$  has been a leading example of the use of the systematics rules given above. Using systematics to identify the high-spin and the low-spin states in  $^{187}\text{Au}$ , it has been possible to deduce that both the high-spin ( $J\pi = 13/2+$ ) and the low-spin ( $\pi = 3/2-$ )  $^{187}\text{Hg}$  isomers are produced in the heavy ion reactions used (the low-spin isomer presumably is populated following the decay of  $^{187}\text{Tl}$ ). We obtain half-lives for these  $^{187}\text{Hg}$  states of 2.4 min ( $13/2+$ ) and 2.2 min ( $3/2-$ ) by following the decay of specific  $\gamma$ -ray lines.

We have evidence for strongly-deformed prolate (Nilsson) states within 600 keV of the weakly-deformed oblate ground state, indicating prolate and oblate shape isomerism that is almost degenerate in energy. We also see the particle-core couplings  $\pi h_{9/2} \otimes ^{186}\text{Pt}(0+, \text{g.s.})$  and  $\pi h_{9/2} \otimes ^{186}\text{Pt}(0+, 475 \text{ keV})$  as triaxial bands with connecting transitions that have EO components. What is still puzzling is that in a picture of triaxially-deformed shapes, the

two bands have almost the same shape. We are considering the possibility that these two bands have very different pairing structure or maybe even very different inertial mass structure; i.e., this may be an example of pairing isomerism or inertial mass isomerism. These two bands will be the subject of a forthcoming letter<sup>f)</sup>.

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<sup>f)</sup> M. A. Grimm, J. L. Wood, and R. W. Fink, Phys. Rev. Lett. (to be submitted)

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We have made considerable progress on the decay scheme of  $^{185}\text{Hg}$  to excited states of  $^{185}\text{Au}$ . The high-spin states populated in  $^{185}\text{Au}$  fit the systematic trend observed in the heavier odd-mass Au isotopes, and it is evident that this population comes from the beta decay of an  $i_{13/2}$  state in  $^{185}\text{Hg}$  to which we assign a half-life of 26 sec and which has been identified as a spherical state by laser spectroscopy<sup>g)</sup> at ISOLDE. The low-spin states that we observe in  $^{185}\text{Au}$  are, for the most part, still not understood. They are unquestionably due to the beta decay of the well-known<sup>h)</sup> strongly-deformed  $^{185}\text{Hg}$  ground state  $1/2^- [521] (T_{1/2} = 51 \text{ sec})$ . We also have evidence for a third beta-decaying state ( $T_{1/2} = 17 \text{ sec}$ ) which we interpret as the strongly-deformed configuration  $7/2^+ [633]$ , for which there is some evidence from laser spectroscopy<sup>g,i)</sup> and systematics (ref. 12). There is much work still to be done on this decay scheme, and it

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<sup>g)</sup> P. Dabkiewicz, et al., J. Phys. Soc (Japan) 44 (1978) Suppl. p. 503

<sup>h)</sup> J. Bonn, et al., Z. Physik A276, 203 (1976)

<sup>i)</sup> H. J. Kluge, private communication (1978); C. Ekström, private communication (1978)

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is clear that to understand fully the decay, data of higher statistical quality will be needed (see the accompanying renewal proposal). The study of the  $^{185}\text{Hg}$  decay scheme is being conducted in collaboration with Dr. E. F. Zganjar of LSU (Physics).

The structural features of excited states in  $^{185,187}\text{Au}$  that are well understood will appear in a paper on the systematic features and theoretical interpretation of the odd-mass Au isotopes.

### 2.3.2 Decay of $^{201\text{m,g}}\text{Po}$ and $^{201\text{m,g}}\text{Bi}$ Isobars

An analysis of the decay of  $^{201\text{m,g}}\text{Po}$  (9 min, 14 min) and  $^{201\text{m,g}}\text{Bi}$  (59 min, 1.8 h) isobars is in progress under the direction of Dr. W. R. Western. The primary area of research this year has been the analysis of the band built upon the  $1/2^+$  shell model intruder state in Bi, and of the 846 keV isomeric transition depopulating this state. This isomeric transition in  $^{201\text{m}}\text{Bi}$  decay (59 min) is the only known " $\ell$ -forbidden" M4 transition in odd-A nuclei and is further expected to be hindered because it is a hole  $\rightarrow$  particle transition. Alpsten and Astner<sup>j)</sup> reported this transition as

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<sup>j</sup> M. Alpsten and G. Astner, Nucl. Phys. A134, 407 (1969)

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probably M4 +  $(54 \pm 20)\%$  E5 with an M4 retardation of more than 1500 compared to the Weisskopf-Moszkowski single-particle estimate. The analysis of this transition is complicated by the existence of a  $^{201}\text{Pb}$   $\gamma$ -ray 1.2 keV higher in energy and populated by the beta decay of both  $^{201\text{m}}\text{Bi}$  and  $^{201\text{g}}\text{Bi}$  (this was unknown to Alpsten and Astner). The amount of contamination from the  $^{201}\text{Pb}$   $\gamma$ -ray was obtained from a comparison of relative intensities in a projected  $\gamma\gamma$  coincidence vs. a  $\gamma$ -singles spectrum, the 846 keV isomeric transition being absent in the coincidence spectrum. With this correction, our experimental value of the K-shell internal conversion coefficient is  $\alpha_K = 0.225 \pm 0.075$ , and this may be compared with theoretical value of  $\alpha_K(\text{M4}) = 0.216$  and  $\alpha_K(\text{E5}) = 6.96 \times 10^{-2}$ . This is consistent with the expectation that the 846 keV isomeric transition in  $^{201}\text{Bi}$  is pure M4, although the possibility of as much as 50% E5 admixture cannot be ruled out within the limits



of uncertainty in the experimental value. If a pure M4 assignment is accepted, this results in a hindrance factor of  $4.5 \times 10^3$ , which is typical of particle-hole transitions of lower multipolarity, but which has not been observed for M4 transitions in odd-A nuclei previously. We are currently looking at additional data that were taken during these experiments to ascertain if we can reduce the uncertainty in the value of  $\alpha_K(847 \text{ keV})$ , and thus the possibility of E5 admixture in this transition.

### 2.3.3 Decay of Odd-Mass $^{185-189}\text{Au}$ Isotopes

During the past year we have obtained conversion electron data on the decay of 8.4 min  $^{187g}\text{Au}$ . The level schemes of  $^{185,187,189}\text{Pt}$  isotopes are still far from being fully worked out. The structure of the nucleus  $^{187}\text{Pt}$  is expected to be extremely complicated due to the possibility<sup>k)</sup> of both

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<sup>k</sup> C. Bourgeois, et al., Cargese Conf. Proceedings, CERN 76-13 (1976); p. 456

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weakly-oblate and strongly-prolate deformed shapes at low energies. We observe a number of transitions with E0 components below 500 keV, suggesting low-energy structures that have very different mean-square radii. The study of levels in  $^{187}\text{Pt}$  is part of the thesis research of Mr. M. A. Grimm.

### 2.3.4 Decay of $^{201,203}\text{At}$ Isotopes

This year we have begun a study of neutron-deficient At isotopes to obtain information on excited states of Po isotopes. The extraction of At activities from the UNISOR integrated target/ion source proved straight-forward. Detailed  $\gamma$ -ray singles and  $\gamma\gamma$ -coincidence spectroscopy is being completed on  $^{203}\text{At}$  decay. These data are under analysis, and the decays of  $^{201,205}\text{At}$  are now under study. The systematics of the excited states in the odd-mass Po isotopes are expected to show similarities to the odd-mass Hg isotopes. A

comparison will provide a general test of the models that we have used for a description of the odd-mass Hg isotopes; and, it will show the difference between the coupling of the two-proton holes (Hg) and two-proton particles (Po) to the various neutron configurations, thus providing a basis for microscopic models. This work constitutes part of the Ph.D. thesis of Mr. Chris Papanicolopoulos.

### 2.3.5 Nuclear Lifetime Measurements

Our on-going program of nuclear lifetime measurements, led by Dr. R. A. Braga, involves the application of the computer-based multiple time analysis technique (MTA) at UNISOR and a study of  $g_{7/2}$  intruder bands in odd-mass Ag isotopes at Georgia Tech. During the past year, the program has progressed from development to application.

The MTA technique for lifetimes in the millisec to microsec region has been used at UNISOR to obtain data following the decay of  $^{187}\text{Hg}$  isomers. However, since by the nature of the method [see the detailed description in our Twelfth Annual Report, ORO-3346-196 (1976)], a complete knowledge of the decay scheme is required, our analysis of the MTA data has been deferred until the decay scheme study is completed. This study, which is part of the Ph.D. thesis of Mr. Marvin Grimm, is expected to be completed in 1978, and the lifetime analysis will then follow immediately.

Measurements of lifetimes of states in  $^{109}\text{Ag}$  believed to be members of the  $g_{7/2}$  intruder band have been performed with delayed coincidence techniques at Georgia Tech. A system, consisting of a plastic scintillator and a Ge(Li) detector, was used to study lifetimes of levels populated in the decay of 13.43 h  $^{109}\text{Pd}$ , sources of which were prepared by the enriched  $^{108}\text{Pd}(n,\gamma)$  reaction in the Georgia Tech Reactor. The evaluation of several runs to date resulted in a value for the lifetime of the  $3/2^+$ , 724.4 keV level, believed

to be the second member of the intruder band, in the range of  $0.3 < \tau < 1.0$  nanosec. However, no lifetime for the  $1/2^+$  band head member at 707.0 keV was obtained. This may be either the result of the lack of statistics, since only 0.0018% of all decays populate this level, or the possibility that a doublet exists<sup>m)</sup> near 707 keV and that the member populated in the decay

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<sup>m</sup> F. E. Bertrand, Nuclear Data Sheets 23, 229 (1978)

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of  $^{109}\text{Pd}$  is not the band head. Additional measurements are in progress.

#### 2.4 International Comparison of $\gamma$ -ray Intensity Standards

The participation of our group in the international comparison of  $\gamma$ -ray emission-rate measurements on  $^{152}\text{Eu}$  sources, organized by the Working Group on Alpha-, Beta-, Gamma-ray Spectroscopy of the International Committee for Radionuclide Metrology (ICRM) under the chairmanship of Dr. K. Debertin (Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany), and administered in this country through the National Bureau of Standards, has been completed and submitted for publication<sup>n)</sup>. In addition, our group has

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<sup>n</sup> K. Debertin, Nucl. Instr. & Meth. (in press, 1978)

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agreed to participate in the international comparison of  $\gamma$ -ray emission-rate measurements on  $^{133}\text{Ba}$  sources organized by the ICRM and furnished by PTB, Braunschweig, West Germany.

#### 3.0 FAST NEUTRON RESEARCH

The work on an enriched  $^6\text{LiD}$  capsule for production of  $14 \pm 2$  MeV neutrons in the Georgia Tech Reactor has been published this year (ref. 2). From correspondence received following publication, there is interest in the use of this method for the preparation of such short-lived (n,2n) products as

10 min  $^{13}\text{N}$ , 110 min  $^{18}\text{F}$ , etc. for nuclear medicine, for fast neutron activation analysis, and for preparation of long-lived (n,2n) products for basic studies. In addition, energy profile of the neutron flux in the H4 position of the reactor has attracted considerable attention. However, the proposed decay scheme study of 8 hour  $^{173}\text{Tm}$ , prepared by the enriched  $^{173}\text{Yb}(n,p)$  reaction in the capsule, has been abandoned, since we learned that this decay is being extensively studied elsewhere. The work on the enriched  $^6\text{LiD}$  capsule constitutes part of the Ph.D. thesis of Mr. Chris Pananicolopoulos.

#### 4.0 X-RAYS FROM RADIOACTIVE SOURCES

##### 4.1 Tables for Handbook of Spectroscopy

We have continued to update our tables of x-ray and Coster-Kronig yields for our chapter in the forthcoming new edition of Handbook of Spectroscopy<sup>o)</sup>. R. W. Fink serves on the Advisory Board of this Handbook and

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<sup>o</sup> R. W. Fink and P. V. Rao, ref. 6, which is a revision of the original chapter, "Tables of Experimental Values of X-ray Fluorescence Yields and Coster-Kronig Transition Probabilities for the K, L, and M Shells,": in Handbook of Spectroscopy, 1st Ed., edited by J. W. Robinson (CRC Publishing Co., West Palm Beach, Florida, Vol. 1, 1974); pp. 219-229

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has arranged for additional chapters on thermal neutron cross sections (ref. 5) and 14 MeV neutron cross sections by S. M. Qaim of Jülich, West Germany, and  $\gamma$ -rays arranged by energy and halflife by G. Erdtmann, also of Jülich. These chapters are useful for neutron activation analysis.

##### 4.2 L-Subshell X-ray Fluorescence and Coster-Kronig Yields at Z = 64 and 67

Our investigation of  $L_2$ - $L_3$  Coster-Kronig transition probabilities and L-subshell x-ray fluorescence yields at Z = 64 and 67, initiated last year, is

nearing completion. Owing to significant improvements both in experimental technique and the experimental determination of pulse shape corrections, values of  $f_{23}$  can be reported to an accuracy not previously attained. The investigation consists of three-parameter coincidence measurements performed with high resolution Si(Li) and intrinsic Ge planar x-ray detectors and sources of 4.7 y  $^{155}\text{Eu}$  and 10.4 h  $^{165}\text{Er}$  and irradiated in the Georgia Tech Reactor.

Previously, corrections in the x-ray gated intensities were made only for contributions from beta-feeding and  $\gamma$ -ray cascades, and subtracting the contribution due to the tail of the unresolved  $K_{\alpha 1}$  x-ray line appearing in the  $K_{\alpha 2}$  gate. The present work indicates the necessity of making such tailing corrections using the true coincidence peak shape rather than the singles shape. To examine this, we applied a self-gated technique (ref.18) utilizing a RaDEF (22 y  $^{210}\text{Pb}$ ) source of 46.5 keV  $\gamma$ -rays.

A preliminary analysis of the data, taken as of September, 1978, yields values of  $f_{23} = 0.150 \pm 0.035$  for  $Z = 64$  and  $0.155 \pm 0.025$  for  $Z = 67$ . The uncertainties quoted here are the variance of the extremes and are not representative of the precision of the measurements. However, The evaluation of the contribution to the L x-ray peaks resulting from the  $K_{\alpha 1}$  tail in the  $K_{\alpha 2}$  gate must take into account the difference between the intensity of L x-ray peaks in coincidence with the  $K_{\alpha 1}$  line and the intensity in coincidence with the  $K_{\alpha 1}$  tail. Therefore, it is necessary in the determination of  $f_{23}$  to evaluate the effect on the L x-ray coincidence spectrum of differing risetimes in the  $K_{\alpha}$  tails. In all reported previous work, the effect on  $f_{23}$  of the coincidence shape of the  $K_{\alpha 1}$  tail, and of risetime differences between the full-energy peak and the tail, which affect the L x-ray coincidence intensities have not been taken into account. This investigation, which is part of the Ph.D. thesis research of Mr. Bruce Gnade, is being completed (ref.11) this year, along with a re-evaluation of previous data, in view of our improvements in tailing and pulse shape corrections (see the accompanying Renewal Proposal).

## 5.0 MISCELLANEOUS TOPICS

### 5.1 Computer Software Improvements

#### 5.1.1 Nuclear Data ND-4420 Codes

With the development of codes (see below) to permit the reading of UNISOR data tapes into the Nuclear Data ND-4420 system in our laboratory, a higher level computing language was needed to facilitate data analysis. For this purpose the conversational, interpretive calculating language ORCAL ("Oak Ridge Calculating Language") has been implemented. This language, combining the floating-point arithmetic package supplied by the Nuclear Data Corporation, with an implementation of FOCAL handler routines into the command set of the ND-812 computer, permits programs written in FOCAL to be run on the ND-4420 system. The ORCAL program has functions for calculating the sine, cosine, log and exponential, and has X-Y plotter and oscilloscope display functions. A routine is also incorporated for reading in data tapes via the Teletype tape reader.

(R. A. Braga and W. R. Western)

#### 5.1.2 CDC-Cyber 70, Model 74 Codes

The major goal of software development in our group this year has been the capability of transferring data from the CDC-Cyber 70 system to the Nuclear Data ND-4420 system in our laboratory. The reasons for doing this include the interactive graphics capabilities of the ND-4420 system, which are not yet available with the CDC-Cyber 70, the convenience of the ND-4420 system, and the potential for interactive data analysis which requires a graphics capability and prompt response from the system.

The most important development this year then is the development of a CDC-Cyber 70 code LISTND which records spectra on magnetic tape using the magnetic tape format of the ND-4420 software. These spectra then can be

examined or analyzed using the ND-4420 system. This code has been particularly useful for storing the hundreds of coincidence spectra generated by the code GATESCN on magnetic tape instead of on a large volume of plots and/or listings. The magnetic tape then can be easily examined for coincidences using the ND-4420 system. Other features include the ability to add spectra with gainshift corrections, to compress spectra, and to split the spectrum into shorter spectra that will fit into the ND-4420. The latter feature is necessary for uncompressed 8K spectra and to use the NUTRAN overlay software of the ND-4420. (NUTRAN is an interpretive type of code which uses FORTRAN type instructions.)

A code, LVLSCN, for producing drawings of nuclear level schemes using a Calcomp plotter has been implemented on the CDC-Cyber 70. The drawings include spins, parities, and energies of the levels, the energy and intensity of the  $\gamma$ -ray transitions, and the coincidence information.

A linear regression CDC-Cyber 70 code for polynomials, FITR, was developed for fitting efficiency curves and determining energy calibrations. It performs weighted or unweighted fits and an optional log-log transformation before fitting.

In addition to the implementation of these codes, a simpler, smaller input code was developed and included in the SKEWGAUS code. The resulting version of SKEWGAUS can accept only Nuclear Data format magnetic tapes or character input and does not include the ability to add spectra together, but it requires less than half the amount of memory of the original version. With the LISTND code, any currently accepted spectral format can be transferred into the Nuclear Data format and the spectra can be added together. (W. R. Western)

## 6.0 EQUIPMENT ADDED DURING 1978

During the past year, equipment purchases have been in the area of support electronics. As a result of experience with the importance of deadtime and pileup corrections involved in our participation in the international intercomparison (PTB, Braunschweig, West Germany and National Bureau of Standards), on gamma-ray intensities in  $^{152}\text{Eu}$  decay, a Berkeley Nucleonics model DB-2 random pulse generator was purchased. This pulser, by simulating counting conditions, permits determination of system deadtime and pileup losses, and its use also excludes the necessity of a radioactive source in the initial setup and checkout of system electronics. In addition, a Canberra model 3002 high voltage power supply was purchased for use with our plastic scintillation detector.

For use in a second Tennecomp system at UNISOR to provide the configurational capability of handling three-parameter experiments, we purchased a Nuclear Data model ND-570 8192-channel, 80 MHz ADC unit. We also provided to UNISOR a Nuclear Data NIM bin providing 6 volts (5 amps) to accommodate three such ADC units in the Tennecomp system.

Our Chemistry Electronics Shop has constructed an electronic controller for a new UNISOR tape transport system for radioactive source collection, and, in addition, the Chemistry Machine Shop fabricated several ion source and miscellaneous items for UNISOR.

(R. A. Braga)



## 7.0 PERSONNEL

### Senior Staff:

Dr. R. W. Fink Professor and Principal Investigator

(1/4 time, 12 months)

Dr. J. L. Wood, Research Scientist and Co-principal Investigator

(October 1, 1972-present; full-time DOE, 12 months, except  
May 10-July 31, 1978 on leave-of-absence while at GSI Darmstadt,  
West Germany)

Dr. R. A. Braga, Research Associate

(October 1, 1974-present; 63% DOE research, 37% teaching for the  
School of Chemistry, 12 months)

Dr. W. R. Western, Research Associate

(November 1, 1976-present; full-time DOE research)

### Graduate Students:

Mr. Chris Papanicolopoulos (Physics). Continuing Ph.D. thesis research.

(1/2 time DOE since June 1, 1975)

Mr. Marvin Grimm (Physics). Continuing Ph.D. thesis research.

(on ORAU fellowship and full-time in residence at UNISOR,  
Oak Ridge National Laboratory)

Mr. Bruce Gnade (Chemistry). Continuing Ph.D. thesis research.

(1/2 time DOE September 1, 1977-December 31, 1977; then 1/2 time  
teaching assistantship due to insufficient funding from DOE)

Mr. Guy J. Tonti, Jr. (Chemistry). New graduate student.

(1/2 time teaching assistant from September 1, 1978)

(B.S. Chem. 1978 from Arizona State Univ., Tempe, Arizona,  
with experience in nuclear chemistry)

## 8.0 LIST OF PUBLICATIONS, PRESENTATIONS AT MEETINGS, &amp; OUTSIDE SEMINARS 1978

- 1) "Decay of  $^{195}\text{Tl}$  (1.13 h) to  $^{195}\text{Hg}$ ," G. M. Cowdy, J. L. Wood, and R. W. Fink, Nuclear Phys. A (in press, 1978) [ORO-3346-215]
- 2) "Production of  $14 \pm 2$  MeV Neutrons in a Reactor with an Enriched  $^6\text{LiD}$  Irradiation Capsule," C. Papanicolopoulos and R. W. Fink, Nuclear Instr. & Meth. 151, 53-60 (1978) [ORO-3346-211]
- 3) "The Decay of Mass Separated  $^{201\text{m},g}\text{Po}$ ," W. R. Western, J. L. Wood, R. A. Braga, and R. W. Fink, Bull. Am. Phys. Soc. 22, 996 (1977) (Rochester, N. Y., October, 1977) [ORO-3346-213]
- 4) "Proton Induced X-ray Emission Multielement Analysis in Biomedical, Environmental, Geological, and Archeological Specimens," invited paper, R. W. Fink, Trans. Am. Nuclear Soc. 27, 206-208 (1977) (San Francisco, California, November, 1977)
- 5) BOOK CHAPTER:  
"Thermal Neutron Reaction Cross Sections," R. W. Fink, in Handbook of Spectroscopy, 2nd Ed. Vol. 3, edited by J. W. Robinson (CRC Publishing Co., West Palm Beach, Florida, in press, 1979) [ORO-3346-206]
- 6) BOOK CHAPTER:  
"Tables of Experimental Values of X-ray Fluorescence and Coster-Kronig Yields for the K-, L-, and M-Shells," R. W. Fink and P. V. Rao, in Handbook of Spectroscopy, 2nd Ed., Vol. 3, edited by J. W. Robinson (CRC Press, Inc., W. Palm Beach, Florida, in press, 1979) [ORO-3346-202]
- 7) BOOK CHAPTER:  
"Analysis of Zinc and Copper," R. W. Fink, Chapt. 2 in Zinc and Copper in Medicine, edited by R. M. Sarper and Z. A. Karcioğlu (C.C. Thomas Publishers, Springfield, Illinois, 1979)
- 8) "Half-lives and Decay of  $^{197}\text{Pb}$  Isomers," M. S. Rapaport, R. W. Fink, L. L. Riedinger, L. L. Collins, and G. D. O'Kelley, Nuclear Phys. A (submitted) [ORO-3346-200]
- 9) "Orbital Electron Capture Ratios in the Decay of  $^{205}\text{Pb}$ ," J. G. Pengra, H. Genz, and R. W. Fink, Nuclear Phys. A (in press, 1978) A302, 1 (1978) [ORO-3346-216]
- 10) "L X-ray Yields from Double Vacancy States in Indium," P. A. Indira, I. J. Unus, P. V. Rao, and R. W. Fink, J. Phys. (London), Atom-Molec. Phys. B. (in press, 1978) [ORO-3346-218]
- 11) "The  $L_2, L_3$  Subshell X-ray Fluorescence and Coster-Kronig Yields at  $Z = 64$  and  $67$ ," B. E. Gnade, R. A. Braga, and R. W. Fink, Z. Physik (to be published) [ORO-3346-226]
- 12) "A New Isomer in  $^{183}\text{Pt}$  and the  $N = 105$  Isotones," A. Visvanathan, E. F. Zganjar, J. L. Wood, R. W. Fink, L. L. Riedinger, F. E. Turner, and H. K. Carter, Phys. Rev. C (Communications) (in press, 1978) [ORO-3346-220]

- 13) "Studies of  $Z = 81$  Transitional Nuclei, I:  $^{197}\text{Pb}$  Decay," L. L. Collins, L. L. Riedinger, G. D. O'Kelley, C. R. Bingham, M. S. Rapaport, J. L. Wood, and R. W. Fink, Nuclear Phys. A (submitted, 1978) [ORO-3346-221]
- 14) "Studies of  $Z = 81$  Transitional Nuclei, II:  $^{193}\text{Pb}$  and  $^{195}\text{Pb}$  Decays," L. L. Collins, L. L. Riedinger, A. C. Kahler, C. R. Bingham, G. D. O'Kelley, J. L. Wood, and R. W. Fink, Nuclear Phys. A (submitted, 1978) [ORO-3346-222]
- 15) "Nuclear Systematics far from the Line of Beta Stability: Their Use, Strengths, and Weaknesses," J. L. Wood, Bull. Am. Phys. Soc. 22, 1024 (1977) [ORO-3346-212]
- 16) "The Region  $77 \leq Z \leq 83$ : Particle-Core Coupling Revisited," J. L. Wood, Bull. Am. Phys. Soc. 23, 628 (1978) (Washington, D. C., April, 1978) [ORO-3346-217]
- 17) "Excited  $0^+$  States, Nuclear Isomerism, and Odd-Nucleon Coupling," J. L. Wood, Bull. Am. Phys. Soc. 23, (1978) (Asilomar, Calif., Nov. (1978)). [ORO-3346-225]
- 18) "Determination of Corrections for Tailing in Low-energy Photon Coincidence Intensity Measurements," B. E. Gnade, R. A. Braga, J. L. Wood, and R. W. Fink, Nuclear Instr. & Meth. [ORO-3346-224]